Evaluation of Canadian Coals for Gasification with Dow Technology

ALBERTA RESEARCH COUNCIL
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EVALUATION OF CANADIAN COALS FOR GASIFICATION WITH DOW TECHNOLOGY

Submitted to

The Canadian Coal Gasification Technical Committee

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Prepared by

G. Kovacik and A.K. Chambers
Coal and Hydrocarbon Processing Department
Alberta Research Council
#1 Oilpatch Drive
Bag #1310
Devon, Alberta
T0C 1E0

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Executive Summary

Integrated Gasification Combined Cycle (IGCC) is potentially the technology of choice for the next generation of coal-fed power plants. The application of coal gasification technology in IGCC plants for production of electricity has advantages in improved efficiency and in reduced pollutant emissions. Coal gasification has other potential uses in the production of hydrogen and petrochemicals.

Existing gasification technologies are based on fixed, fluidized or entrained bed reactors operating at various reactor conditions. The suitability of a certain coal for a particular technology may depend on its physical and chemical properties. Examples of entrained flow gasifiers include Dow (coal-water slurry feed), Texaco (coal-water slurry feed) and Shell (dry, pulverized feed) technologies. The British Gas-Lurgi gasifier (dry, crushed feed) is an example of a fixed bed gasifier. All four gasifiers are oxygen blown with slagging ash removal and are candidate gasifiers for IGCC plants.

This study was performed to obtain an initial assessment of the suitability of several Canadian coals in the Dow gasification technology. Analyses of Byron Creek (Esso Resources Canada Ltd.), Highvale (TransAlta Utilities Corp.), Paint Earth (Alberta Power Ltd.), Genesee (Edmonton Power Ltd.), Costello (Prairie Coal Ltd.), and Minto (New Brunswick Power) coals were sent to Dow for evaluation in their gasification technology. Performance estimates included heat and mass balances around the IGCC plant and prediction of the gasifier product gas composition. No gasification or coal/ water slurry preparation experiments were performed during these evaluations. A previous study (Kovacik and Chambers, 1988) detailing the predicted performance of five Canadian coals in Shell, Texaco, and British Gas technologies was used as a basis of comparison for the Dow technology.

All six coals included in this study were judged suitable for the Dow gasification technology. Flux additives (limestone) that reduce slagging temperatures were needed for Byron Creek (2.9 wt% addition, as rec'd coal

basis), Paint Earth (4.3 wt%), and Genesee (5.1 wt%) coals. Gasifier cold gas efficiencies, based on higher heating value, varied from 78.5%, for Byron Creek coal, to 57.3% for Costello lignite. Cold gas efficiency increased with increasing heating value of the coal and increasing slurry solids loading, (i.e. increasing slurry heating value). When the four competing technologies were compared using Highvale coal as the gasifier feed the predicted cold gas efficiencies, in increasing order, were; Texaco (68.3%), Dow (68.5%), Shell (82.9%) and British Gas (91.4%).

When the overall IGCC plant thermal efficiencies are compared, the relationship between coal/slurry properties and efficiency was not so evident. IGCC thermal efficiencies, based on coal higher heating value varied from a low of 37.1% for Paint Earth to a high of 40.4% for Costello lignite. The other four coals were grouped between 39 and 40%.

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1.0 Introduction

1.1 Background

The application of coal gasification technology in IGCC plants for the production of electricity has advantages in improved thermal efficiency, reduced pollutant emissions and staged installation of new capacity. The technology of combining a coal gasifier with a gas fired turbine and a steam cycle has been demonstrated at full scale by Destec Energy (Dow) at Plaquemaine, Louisiana. Because of its advantages, the IGCC technology is potentially the technology of choice for the next generation of coal-based power stations.

Dow, Texaco, Shell and British Gas have competing gasification technologies in advanced stages of development. The Dow and Texaco processes use an entrained flow reactor with coal/water slurry feed, the British Gas-Lurghi process is a slagging fixed-bed reactor and Shell's process is an entrained flow reactor with dry feed. Further details of these gasifiers are available in previous reports submitted to the Alberta Office of Coal Research and Technology and the Canadian Coal Gasification Technical Committee (Kovacik and Chambers, 1988 and TransAlta, 1987) or in Elliott, 1981 for Texaco and British Gas and Krewinghaus and Nager, 1987 for Shell. Depending on the physical and chemical properties of the feed coal, the suitability of a technology to a coal will vary. Each company has performed sufficient research and development to allow the preliminary evaluation and prediction of the performance of a candidate coal in their gasifier from laboratory analyses of small samples of coal. Six members of the Canadian Gasification Technical Committee agreed to submit analyses of their coal for evaluation as a feedstock in the Dow (or Destec) gasification process. This report details the results of the Dow evaluation and compares these results with previous work (Kovacik and Chambers, 1988).

1.2 Objective

The objectives of this study were to:

- have Dow assess the performance of their gasification technology using six Canadian coals; and
- review the assessment reports and prepare a covering report describing the results of these tests and comparing them with previous work.

1.3 Scope

This report summarizes the results of a screening study of six Canadian coals and their suitability for utilization in the Dow gasification technology. The technology examined was a coal/water slurry fed, two stage, entrained flow gasifier. This screening study provides a basis for future coal testing and technology assessment for these coals and an indication of the relative performance of the different coals.

2.0 Methodology

2.1 Sample Acquisition and Analysis

The analyses requested by Dow were performed in the analytical facilities of the Coal and Hydrocarbon Processing Department, Alberta Research Council, Devon. The coals tested and the companies which contributed to this project were Byron Creek (Esso Resources Canada Ltd.), Highvale (TransAlta Utilities Ltd.), Paint Earth (Alberta Power Ltd.), Genesee (Edmonton Power Ltd.), Costello (Prairie Coal Ltd.), and Minto (New Brunswick Power Ltd.).

2.2 Assessment of Performance

Dow assessed the coals for suitability in their process and performed heat and mass balances about the gasifier. The evaluation reports from Dow are attached as Appendix A. In addition Dow predicted the performance for a complete IGCC plant.

The evaluations reported by Dow were performed based on analytical results from small (gram size) coal samples only and these assessments did not involve any actual experimental gasification or coal/water slurry preparation studies. These results should therefore be viewed as screening studies to give an initial assessment of performance only. This assessment could form the basis for further more detailed studies.

3.0 Results and Discussion

3.1 Sample Analysis Results

The results of the analyses performed by the Alberta Research Council and forwarded to Dow are summarized in Appendix B. Table 1 summarizes the analyses which were performed for the evaluation of suitability of the coals. Where the selected coals were the same as for previous studies (Byron Creek, Highvale and Paint Earth, Kovacik and Chambers, 1988) identical analyses were used to facilitate consistant comparisons of the technologies.

3.2 Dow Process

The Dow process is an oxygen blown, slagging, two stage, entrained-flow gasifier which uses a coal-water slurry to pressurize and introduce the coal into the gasifier. Limestone ($CaCO_3$) may be added as a flux to provide adequate slagging characteristics for removal of molten ash from the gasifier. Two coal properties of importance were the ash fusion characteristics and the total moisture content of the coal-water slurry formed. For Byron Creek, Paint Earth,

and Genesee coals, addition of a fluxing agent ($CaCO_3$) would be required tc reduce ash fusion temperatures to those suitable for the Dow slagging gasifier. This fluxing agent addition varied from 0 to 5.1 wt% based on as received coal feed. The predicted solids concentration of the coal/water feed slurries varied from a low of 52.0 wt% for Costello to a high of 66.7 wt% for Byron Creek and Minto. Both the fluxing agent and the slurry water decrease the gasifier efficiency by increasing energy lost in the ash and water vapor leaving the reactor. Therefore, more coal must be burned to reach the desired gasifier operating temperature if the slurry has a high water content or when fluxing agents are required.

Table 1: Analyses Performed for Gasification Evaluation

Analysis	Dow
Proximate	x
Ultimate	x
Chlorine content	x
Calorific value	x
Ash analysis	x
Ash fusion temperatures	x
Equilibrium moisture	x

Table 2 summarizes the predicted performance of the six coals in the Dow gasifier. Further details are given in Appendix A. Although the gasifier carbon conversion was not reported, calculated values, based on a carbon balance performed on the input/output data, were all between 99.2 and 99.4%. A flux additive (limestone), for reduction of ash slagging temperature, was needed for

Byron Creek (2.9 wt% addition, as rec'd coal basis), Paint Earth (4.3 wt%), and Genesee (5.1 wt%) coals. This addition of flux would have a negative impact on the overall process due to increased costs as well as increased ash loading. Gasification cold gas efficiencies, based on higher heating value, varied from 78.5% for Byron Creek coal, to 57.3% for Costello lignite. Gasifier cold gas efficiency increased with both increasing heating value of the coal and increasing slurry solids loading, that is increasing slurry heating value. In order for the gasifier to maintain sufficient operating temperature to slag the ash with the increasing ash and water content in the feed, more of the coal carbon must be converted to CO_2. Thus the production of combustible gas (H_2 plus CO) decreased with increasing ash and water content of the gasifier feed. This is also reflected in reduced gasifier cold gas efficiency.

Table 2: Summary of Dow Gasifier Performance

	Byron Creek	Highvale	Paint Earth	Genesee	Costello	Minto
GASIFIER FEED, (kg)						
Coal, as rec'd	1.0	1.0	1.0	1.0	1.0	1.0
Coal ash	0.112	0.101	0.161	0.170	0.087	0.164
Coal H_2O	0.011	0.139	0.158	0.190	0.244	0.007
Oxygen	0.934	0.634	0.580	0.596	0.554	0.830
Steam/H_2O[1]	0.498	0.435	0.457	0.460	0.454	0.489
Flux, $CaCO_3$	0.029	0.0	0.043	0.051	0.0	0.0
Slurry Concent'n (wt% dry solids)	66.67	60.00	59.00	57.00	52.00	66.67
Slurry HHV (MJ/kg of slurry)	20.62	15.61	13.96	13.78	13.20	19.59
PRODUCTS						
Dry gas, (m^3 @ 15.6 C)	2.38	1.85	1.63	1.60	1.55	2.14
Composition, mol%						
CO	50.23	42.39	37.91	39.07	40.29	49.06
H_2	33.63	37.33	37.91	37.02	37.54	35.23
CO_2	12.63	17.39	21.11	21.01	19.09	12.39
CH_4	0.33	0.17	0.11	0.11	0.13	0.34
Other	3.18	2.72	2.97	2.85	2.95	2.98
HHV dry gas MJ/m^3[2]	10.20	9.63	9.14	9.15	9.39	10.24
Cold Gas Eff.[3] (% HHV)	78.50	68.50	63.00	60.60	57.30	74.60

1) does not include cooling water requirements
2) calculated from dry gas composition - see Appendix C
3) calculated as in Appendix C; higher heating values from Appendix B

When the overall IGCC plant thermal efficiencies, summarized in Table 3, were compared, the relationship between coal/slurry properties and IGCC plant efficiency was not clear nor pronounced. Thermal efficiencies, based on coal higher heating value, varied from a low of 37.1% for Paint Earth to a high of 40.4% for Costello lignite. The other four coals were grouped between 39 to 40%. In an IGCC plant, the amount of energy available for recovery in the gas turbine would be proportional to gasifier cold gas efficiency. The high IGCC thermal efficiency reported for the Costello lignite despite the low gasifier cold gas efficiency was surprising. The relative amount of electricity generated in the gas turbine compared to the steam turbine is highest for Costello coal (Table 3). Also, although Paint Earth coal generates more combustible gas energy per kg than Costello, Table 3 gives a gas turbine output 7.5% lower than for Costello. The most plausible explanation is that the Dow gasification process was designed for Texas lignite and, as a result, the steam generation and condensate heating integration between the gasification and combined cycle blocks was optimized for the lignite coal. Another factor could be coal reactivity. The higher rank coals (Byron Creek and Minto) would be less reactive and thus put increased demand on the char recycle system, which may result in decreased efficiency. However, the reported parasitic power consumption for the low rank coals was similar to that of the higher rank coals, except for Minto which has a much higher sulfur content. Discussions with representatives of Dow failed to satisfactorily resolve the question.

Table 3: Summary of Dow IGCC Performance

	Byron Creek	Highvale	Paint Earth	Genesee	Costello	Minto
GASIFIER FEED, (kg)						
Coal, as rec'd	1.0	1.0	1.0	1.0	1.0	1.0
Oxygen	0.934	0.634	0.580	0.596	0.554	0.830
Slurry Concent'n (wt% solids)	66.67	60.00	59.00	57.00	52.00	66.67
Slurry HHV (MJ/kg coal)	30.59	22.39	19.93	19.58	19.19	29.18
IGCC POWER PLANT						
OUTPUT, kW hr/kg coal						
Gas Turbine	2.19	1.62	1.35	1.48	1.46	2.14
Steam Turbine	1.58	1.07	0.93	0.90	0.86	1.42
INTERNAL USE						
Oxygen Plant	0.27	0.19	0.17	0.18	0.16	0.26
Other	0.09	0.06	0.05	0.05	0.05	0.11
% of Net Power	10.56	10.25	10.68	10.70	10.00	11.60
NET POWER	3.41	2.44	2.06	2.15	2.10	3.19
THERMAL EFFICIENCY (HHV basis)	40.03	39.15	37.07	39.43	40.41	39.26

3.3 Comparison of the Texaco, British Gas, Shell and Dow Gasifiers

Direct comparison of the data from the four gasifier vendors was complicated by the different systems of units used and different reporting formats. To compare the performance for the four gasifiers, the supplied performance predictions were converted to a standard format for Highvale coal, which was found suitable for all four gasifiers. Table 4 compares the feed required and products for the four gasifiers per kilogram of as received coal fed, calculated from the data supplied in the Appendix A and Kovacik and Chambers, 1988. Appendix C summarizes the calculation formulae used in the preparation of this table. The approximate cold gas efficiency based on the higher heating value (HHV) of the coal and product gas at 15.6°C (60°F) is given. These efficiencies do not account for differences in internal plant power consumption between the gasifiers.

The technologies in order of increasing cold gas efficiency for Highvale coal were Texaco (68.3%), Dow (68.5%), Shell (82.9%) and British Gas (91.4%). The volume of dry gas produced per kilogram of coal was similar for all four technologies. The technologies in order of increasing product gas higher heaving value were Texaco (8.81 MJ/m^3), Dow (9.63 MJ/m^3), Shell (11.19 MJ/m^3) and British Gas (12.54 MJ/m^3). Carbon conversion for all four gasifiers was above 99%. Some advantages and disadvantages of each technology are also noted in Table 4. Although the British Gas unit has the highest efficiency, it has disadvantages of fines intolerance, tar import required for Highvale coal and flux additive requirement. The Texaco gasifier suffers from low efficiency and a flux requirement. In an IGCC application, the low efficiency may be partially offset by steam generated in the process. The Texaco unit requires a flux to reduce slagging temperature partially because it has an insulated reactor unlike the Shell unit which is a water wall. Thus the Texaco gasifier has a lower maximum operating temperature to prevent degradation of the insulation. The Shell gasifier has good efficiency, low steam consumption, high

fines tolerance and no stated requirement for a flux additive. The Dow gasifier required no flux additive for the Highvale coal. Gasifier cold gas efficiency for the Dow process was similar to Texaco's despite the higher solids concentration assumed by Dow (60 wt% versus 56.3 wt%) and the two stage operation of the Dow gasifier.

Tables 5 and 6 compare the performance of the four gasifiers for the Byron Creek and Paint Earth coals. The ranking of the gasifiers in terms of cold gas efficiency and product gas heating value was the same as discussed for Highvale coal.

The composition of the product gas, specifically the H_2/CO ratio may have importance for applications other than IGCC (e.g. for production of petrochemicals). The H_2/CO mole ratio for Highvale coal in Shell and British Gas were both about 0.40. For Texaco and Dow the ratio was about 0.89. This higher hydrogen content is likely due to the higher water input slurry feed and higher conversion of coal carbon to CO_2.

Table 4: Comparison of Gasifier Performance with Highvale Coal

	Texaco	British Gas	Shell	Dow
Gasifier Feed (kg)				
Coal (as received)	1	1	1	1
Oxygen	0.736	0.441	0.638	0.634[5]
Steam[1]	0.776[4]	0.273	0.026	0.667
Flux	0.009	0.025	0.0	0.0
Coal moisture + ash (wt%)	28.4	27.52	23.53	23.95
Slurry Concentration (wt% dry solids)	56.3	-	-	60.0
Products				
Dry gas (m^3 at 15.6°C)	1.617	1.540	1.651	1.85
Composition (vol%)				
CO	38.79	63.09	66.31	42.39
H_2	34.60	25.07	27.03	37.33
CO_2	25.99	3.20	1.55	17.39
CH_4	0.0	5.27	0.02	0.17
Others	0.62	3.37	5.09	2.72
HHV dry gas (MJ/m^3)[2]	8.81	12.54	11.19	9.63
Cold gas efficiency[3] (% based on HHV)	68.3	91.4	82.9	68.5
Advantages	- advanced stage of development	- high efficiency	- no flux required - good efficiency	- no flux required
Disadvantages	- low gasifier efficiency - flux required	- low fines tolerance - briquetting required for some coals - high flux requirements - tar handling required	- requires finer grind than conventional pulverized - pre-drying of coal required	- low gasifier efficiency

1) does not include cooling water requirements
2) calculated from dry gas composition - see Appendix C
3) calculated as in Appendix C; assumed HHV (maf) for Highvale of 29.15 MJ/kg
4) assumed 56.3 wt% solids loading in slurry
5) assumed 60.0 wt% solids loading in slurry

Table 5: Comparison of Gasifier Performance with Byron Creek Coal

	Texaco	British Gas	Shell	Dow
Gasifier Feed (kg)				
Coal (as received)	1	-	1	1
Oxygen[1]	0.901[4]	-	0.954	0.934
Steam[1]	0.501[4]	-	0.129	0.510
Flux	0.032	-	0.0	0.029
Coal moisture + ash (wt%)	16.85	-	12.36	0.1236
Slurry Concentration (wt % dry solids)	66.6	-	-	66.67
Products				
Dry gas (m^3 at 15.6°C)	2.07	-	2.24	2.38
Composition (vol%)				
CO	45.38	-	65.61	50.23
H_2	34.99	-	27.24	33.63
CO_2	19.25	-	1.57	12.63
CH_4	0.10	-	0.00	0.33
Others	0.28	-	5.58	3.18
HHV dry gas (MJ/m^3)[2]	9.81	-	11.12	10.20
Cold gas efficiency[3] (% based on HHV)	70.1	-	81.6	78.5

1) does not include cooling water requirements
2) calculated from dry gas composition - see Appendix C
3) calculated as in Appendix C; assumed HHV (maf) for Byron Creek of 34.82 MJ/kg
4) assumed 66.6 wt% solids loading in slurry

Table 6: Comparison of Gasifier Performance with Paint Earth Coal

	Texaco	British Gas	Shell	Dow
Gasifier Feed (kg)				
Coal (as received)	1	-	1	1
Oxygen	0.784	0.378	0.523	0.580
Steam[1]	1.193[4]	0.234	0.0	0.740
Flux	0.028	0.108	0.0	0.043
Coal moisture + ash (wt%)	37.11	30.99	39.14	0.3189
Slurry Concentration (wt % dry solids)	45.6	-	-	59.0
Products				
Dry gas (m^3 at 15.6°C)	1.30	1.39	1.30	1.63
Composition (vol%)				
CO	26.14	59.14	65.43	37.91
H_2	31.49	25.40	26.02	37.91
CO_2	41.71	6.50	2.23	21.11
CH_4	0.0	5.28	0.01	0.10
Others	0.66	3.68	6.32	2.97
HHV dry gas (MJ/m^3)[2]	6.92	12.38	10.96	9.14
Cold gas efficiency[3] (% based on HHV)	49.5	86.2	80.6	63.0

1) does not include cooling water requirements
2) calculated from dry gas composition - see Appendix C
3) calculated as in Appendix C; assumed HHV (maf) for Paint Earth of 28.98 MJ/kg
4) assumed 58.5 wt% solids loading in slurry

4.0 Conclusions

Six Canadian coals have been evaluated for their suitability and performance in the Dow gasification process. The following conclusions were drawn from a review of these evaluations:

1. All six coals evaluated were judged to be suitable feedstocks for the Dow gasification technology.

2. Flux additives to improve ash slagging characteristics and therefore gasifier operation would be required for Byron Creek, Paint Earth and Genesee coals.

3. Predicted gasifier cold gas efficiencies for the six coals evaluated, in increasing order, were; 57.3% for Costello, 60.6% for Genesee, 63.0% for Paint Earth, 68.5% for Highvale, 74.6% for Minto, and 78.5% for Byron Creek.

4. Predicted IGCC plant thermal efficiencies (HHV) for the six coals evaluated, in increasing order, were; 37.1% for Paint Earth, 39.4% for Genesee, 39.2% for Highvale, 39.3% for Minto, 40.0% for Byron Creek, and 40.4% for Costello.

5.0 Recommendations

The results summarized in this report were gained from manufacturer evaluations based on laboratory data only. The following are recommendations for further work:

1. As no gasification experiments were performed in this project, the data supplied should be used for initial evaluation only. Actual gasification testing is recommended for the coals and technologies of interest prior to process design.

2. The effect of flux additives on overall process economics and operability should be investigated before process selection is made.

3. The performance of the Dow gasifier was sensitive to the coal concentration of the slurry feed. Methods to maximize slurry coal concentration should be investigated.

4. High IGCC thermal efficiency results for the Costello lignite were reported. These results should be confirmed before any gasification process selection is made for this coal.

6.0 References

Elliot, M.A. 1981, 'Chemistry of Coal Utilization - 2nd Supplementary Volume', John Wiley and Sons, New York.

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Krewinghaus, A.B. and Nager, M., 1987, 'Start-up and Operating Experience with the Shell Coal Gasification Demonstration Plant', Seventh Annual EPRI Conference on Coal Gasification, Palo Alto, CA., October.

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APPENDIX A

DESTEC ENERGY

2500 CITY WEST BLVD
PO BOX 4411
HOUSTON, TEXAS 77210-4411
(713) 974-8200

December 11, 1990

Gary Kovacik
Alberta Research Council
Coal and Hydrocarbon Processing Department
P. O. Box 429
Nisku, Alberta Canada TOC 2GO

RE: Performance of Dow Gasification Technology, Reference No 2860-G1-1

Dear Mr. Kovacik:

The expected performance of the Dow gasification process in an integrated gasification combined cycle, IGCC, mode has been evaluated for the coals supplied. Steam generation and condensate heating requirements for the process is integrated between the gasification and combined cycled blocks to effectively utilize the heat available in these process areas. Sulfur removal is 98% for all coals. The gas turbine performance is based on the General Electric frame 7F for ambient conditions of -18 C and 700 mm of Hg for all coals except the Minto coal. For the Minto coal, ambient conditions of 0 C and 760 mm of Hg were used. A NOX emmission of 48 nanograms/joule is assumed to be accomplished with low NOX burners or SCR in the gas turbine heat recovery unit. The condensing pressure for the steam turbine was assumed to be 25.4 of Hg for all cases.

A block diagram is enclosed giving the basic process streams for the IGCC model utilized for the evaluation. Stream data for each of the coal cases is given in Tables 1 through 6. The performance is strongly dependent on the level of solids loading in the coal slurry fed to the Dow Gasifier, i.e. overall process efficiency increases with increasing slurry concentration. In the current study solid loadings of 58 to 59 weight % solids were assumed for the subbituminous coals Costello, Genesee, Highvale and Paint Earth. Recent research information indicate that with additional slurry treatment, slurry concentrations approaching 70 weight % solids are possible for subbituminous coals. Therefore, significant improvement in the heat rate for the subbituminous coals could be realized for an IGCC facility utilizing higher slurry concentrations.

If you have any questions regarding this data, please call me at (713) 974-8249.

Sincerely yours,

David L. Breton

David L. Breton
Manager of Technology

DLB/bf

Enclosure

DOW

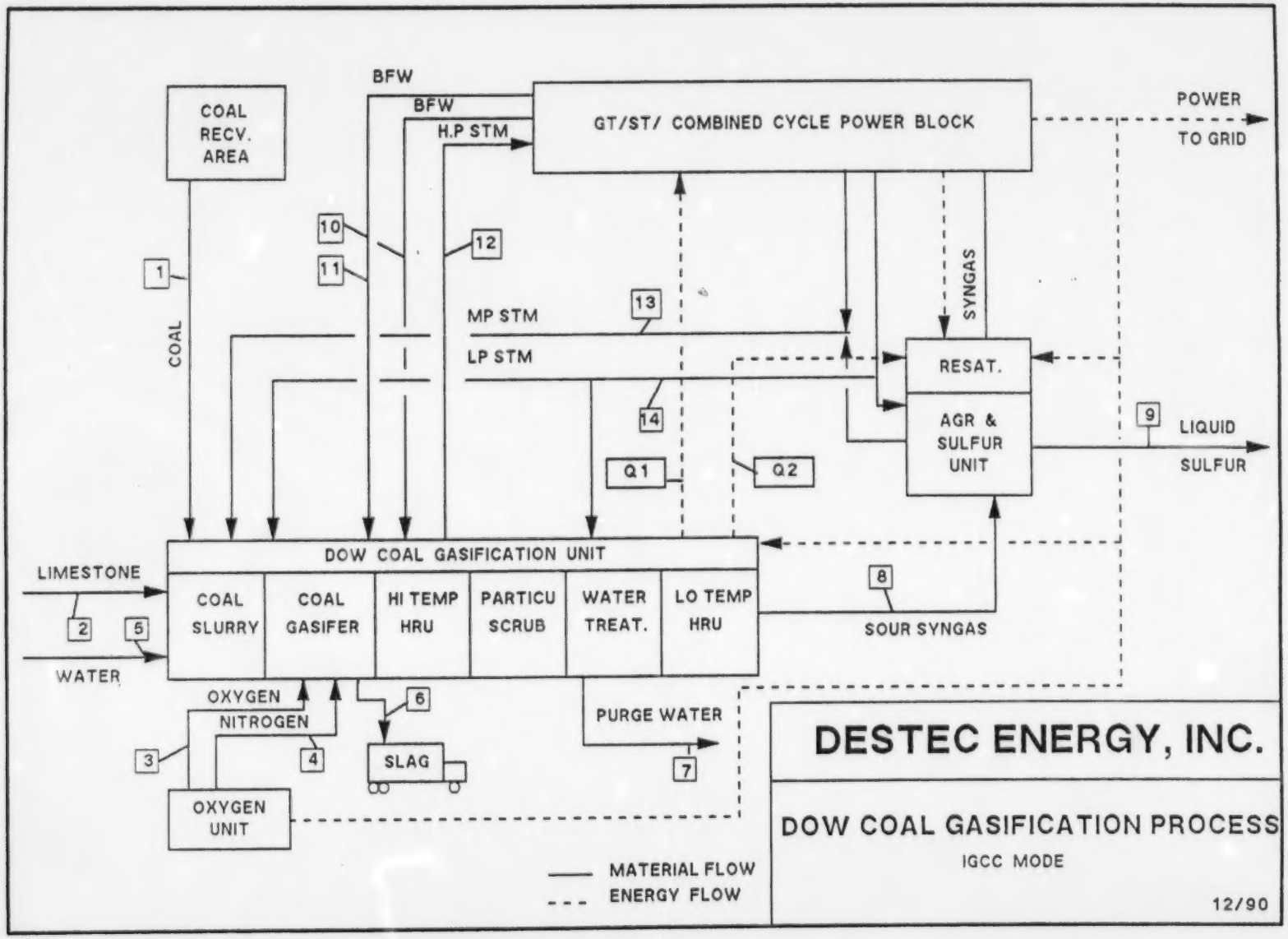
COAL RECV. AREA
BFW
BFW
H.P STM
GT/ST/ COMBINED CYCLE POWER BLOCK
POWER
TO GRID
10
11
12
1
COAL
MP STM
13
LP STM
SYNGAS
RESAT.
AGR & SULFUR UNIT
9
LIQUID
SULFUR
14
Q1
Q2
DOW COAL GASIFICATION UNIT
LIMESTONE
2
5
WATER
COAL SLURRY
COAL GASIFER
HI TEMP HRU
PARTICU SCRUB
WATER TREAT.
LO TEMP HRU
8
SOUR SYNGAS
OXYGEN
NITROGEN
3
4
6
SLAG
PURGE WATER
7
OXYGEN UNIT
MATERIAL FLOW
ENERGY FLOW
DESTEC ENERGY, INC.
DOW COAL GASIFICATION PROCESS
IGCC MODE
12/90

TABLE 1
MATERIAL AND ENERGY BALANCE FOR BYRON CREEK
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream	kg/hr
1. Coal	71076
1.1 Dry Solids	70230
Moisture	846
2. Limestone	2051
3. 95% Oxygen	70370
3.1 O_2	66360
3.2 N_2 + A	4010
4. Nitrogen	1360
5. Water Makeup	18220
6. Slag	12533
6.1 Dry Solids	9318
6.2 Moisture	3215
7. Water Discharge	2371
8. Sour Snygas	152983
8.1 H_2	4845
8.2 CO	100500
8.3 CH_4	380
8.4 H_2S	140
8.5 COS	1
8.6 CO_2	40050
8.7 H_2O	673
8.8 Other	6394
Pressure = 22.4 BAR Temperature = 85 °C	
9. Sulfur	131

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	44480
11.	BFW	117	344	163300
12.	STM	117	358	203500
13.	STM	31	397	399
14.	STM	17	240	24030

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	195	55510
BFW (Q2)	131	39090

Power Balance		MW
Gross		
Gas Turbine		155.5
Stm Turbine		112.5
	Total	268.0
Used		
Oxygen		19.5
Gasification		2.5
Station Power		4.1
	Total	26.1
Net		241.9
Overall Efficiency		
% (HHV)		40.03
% (LHV)		41.27

TABLE 2
MATERIAL AND ENERGY BALANCE FOR HIGHVALE
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream		kg/hr
1.	Coal	99660
	1.1 Dry Solids	85840
	Moisture	13820
2.	Limestone	None
3.	95% Oxygen	67000
	3.1 O_2	63180
	3.2 N_2 + A	3820
4.	Nitrogen	1360
5.	Water Makeup	9571
6.	Slag	13800
	6.1 Dry Solids	10260
	6.2 Moisture	3540
7.	Water Discharge	4421
8.	Sour Snygas	165637
	8.1 H_2	5870
	8.2 CO	92570
	8.3 CH_4	213
	8.4 H_2S	72
	8.5 COS	1
	8.6 CO_2	60200
	8.7 H_2O	736
	8.8 Other	5975
	Pressure = 22.4 BAR Temperature = 85 °C	
9.	Sulfur	67

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	39360
11.	BFW	117	344	140600
12.	STM	117	358	174500
13.	STM	31	397	577
14.	STM	17	240	38680

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	195	88400
BFW (Q2)	148	41500

Power Balance		MW
Gross		
Gas Turbine		161.1
Stm Turbine		106.3
	Total	267.4
Used		
Oxygen		18.5
Gasification		1.8
Station Power		4.0
	Total	24.3
Net		243.1
Overall Efficiency		
% (HHV)		39.15
% (LHV)		40.56

TABLE 3
MATERIAL AND ENERGY BALANCE FOR PAINT EARTH
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream	kg/hr
1. Coal	121530
1.1 Dry Solids	102300
Moisture	19230
2. Limestone	5223
3. 95% Oxygen	74700
3.1 O_2	70450
3.2 N_2 + A	4250
4. Nitrogen	1360
5. Water Makeup	7530
6. Slag	30510
6.1 Dry Solids	22690
6.2 Moisture	7820
7. Water Discharge	6420
8. Sour Snygas	181514
8.1 H_2	6378
8.2 CO	88580
8.3 CH_4	130
8.4 H_2S	406
8.5 COS	5
8.6 CO_2	78240
8.7 H_2O	789
8.8 Other	6986
Pressure = 22.4 BAR	
Temperature = 85 °C	
9. Sulfur	381

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	51810
11.	BFW	117	344	176900
12.	STM	117	358	221400
13.	STM	31	397	835
14.	STM	17	240	52540

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	195	100000
BFW (Q2)	167	44770

Power Balance		MW
Gross		
Gas Turbine		164.0
Stm Turbine		113.1
	Total	277.1
Used		
Oxygen		20.7
Gasification		2.4
Station Power		4.2
	Total	27.3
Net		249.9
Overall Efficiency		
% (HHV)		37.07
% (LHV)		38.52

TABLE 4
MATERIAL AND ENERGY BALANCE FOR GENESSE
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream	kg/hr
1. Coal	114720
1.1 Dry Solids	92920
Moisture	21800
2. Limestone	5823
3. 95% Oxygen	72510
3.1 O_2	68380
3.2 N_2 + A	4130
4. Nitrogen	1360
5. Water Makeup	4980
6. Slag	30900
6.1 Dry Solids	22980
6.2 Moisture	7920
7. Water Discharge	5700
8. Sour Snygas	170347
8.1 H_2	5781
8.2 CO	84760
8.3 CH_4	128
8.4 H_2S	262
8.5 COS	3
8.6 CO_2	72230
8.7 H_2O	959
8.8 Other	6224
Pressure = 22.4 BAR Temperature = 90 °C	
9. Sulfur	246

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	37800
11.	BFW	117	352	181400
12.	STM	117	358	212600
13.	STM	31	397	724
14.	STM	17	240	41980

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	194	102900
BFW (Q2)	157	40480

Power Balance		MW
Gross		
Gas Turbine		169.3
Stm Turbine		103.4
	Total	272.7
Used		
Oxygen		20.1
Gasification		2.3
Station Power		3.9
	Total	26.3
Net		246.4
Overall Efficiency		
% (HHV)		39.43
% (LHV)		40.85

TABLE 5
MATERIAL AND ENERGY BALANCE FOR COSTELLO
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream	kg/hr
1. Coal	114900
1.1 Dry Solids	84570
Moisture	30330
2. Limestone	None
3. 95% Oxygen	67540
3.1 O_2	63690
3.2 N_2 + A	3850
4. Nitrogen	1360
5. Water Makeup	None
6. Slag	13720
6.1 Dry Solids	10200
6.2 Moisture	3520
7. Water Discharge	14810
8. Sour Snygas	161628
8.1 H_2	5679
8.2 CO	84740
8.3 CH_4	158
8.4 H_2S	627
8.5 COS	8
8.6 CO_2	63570
8.7 H_2O	709
8.8 Other	6137
Pressure = 22.4 BAR Temperature = 85 °C	
9. Sulfur	588

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	34050
11.	BFW	117	352	158700
12.	STM	117	358	187200
13.	STM	31	397	800
14.	STM	17	240	40450

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	193	92940
BFW (Q2)	153	38920

Power Balance		MW
Gross		
Gas Turbine		167.4
Stm Turbine		98.3
	Total	265.7
Used		
Oxygen		18.7
Gasification		2.0
Station Power		3.7
	Total	23.4
Net		241.3
Overall Efficiency		
% (HHV)		40.41
% (LHV)		42.01

TABLE 6
MATERIAL AND ENERGY BALANCE FOR MINTO
ONE MODULE - 1 GE-7F GAS TURBINE

MATERIAL

Process Stream		kg/hr
1.	Coal	77090
	1.1 Dry Solids	76550
	Moisture	540
2.	Limestone	None
3.	95% Oxygen	67810
	3.1 O_2	63950
	3.2 N_2 + A	3860
4.	Nitrogen	1360
5.	Water Makeup	21800
6.	Slag	17360
	6.1 Dry Solids	12900
	6.2 Moisture	4460
7.	Water Discharge	2390
8.	Sour Snygas	153016
	8.1 H_2	4958
	8.2 CO	95910
	8.3 CH_4	379
	8.4 H_2S	6575
	8.5 COS	65
	8.6 CO_2	38370
	8.7 H_2O	886
	8.8 Other	5873
	Pressure = 22.4 BAR Temperature = 90 °C	
9.	Sulfur	6137

BFW/Stm Stream	Mtl	BAR	°C	kg/hr
10.	BFW	124	170	43440
11.	BFW	117	344	163300
12.	STM	117	358	202400
13.	STM	31	397	2610
14.	STM	17	240	13850

Heat Flow	Avail Temp °C	Avail MJ/hr
Resaturator (Q1)	195	49240
BFW (Q2)	140	41400

Power Balance		MW
Gross		
Gas Turbine		165.2
Stm Turbine		109.2
	Total	274.4
Used		
Oxygen		19.7
Gasification		4.6
Station Power		4.1
	Total	28.4
Net		246.0
Overall Efficiency		
% (HHV)		39.26
% (LHV)		40.56

APPENDIX B

	Byron Creek[1] Coal	Highvale[1] Coal	Paint Earth[2] Coal	Genesee Coal	Costello Coal	Minto Coal
Proximate Analysis [wt% as rec'd]						
Moisture	1.19	13.87	15.82	19.00	26.40	0.70
Ash	11.17	10.08	16.07	17.00	8.70	16.44
Volatile	23.32	30.66	29.46	24.40	30.60	33.43
Fixed Carbon	64.32	45.39	38.64	39.60	34.30	49.43
Ultimate Analysis [wt% as rec'd]						
Carbon	76.48	56.85	48.71	48.60	47.18	67.69
Hydrogen	4.28	5.08	5.16	5.21	6.17	4.30
Nitrogen	1.44	0.80	1.13	0.64	0.81	0.84
Chloride	0.01	0.10	0.11	0.10	n/d	n/d
Sulfur	0.19	0.07	0.32	0.22	0.52	8.12
Oxygen, by diff.	6.43	27.12	28.57	28.20	36.62	2.61
Heating Value [BTU/lb, dry]	13311.00	11192.00	10184.00	10403.00	10923.00	12645.00
Equilibrium Moisture [wt%]	2.42	19.71	25.51	24.02	30.00	1.00
Ash Analysis [wt% as oxide]						
Silicon	47.98	40.28	51.71	57.86	32.80	28.89
Aluminum	30.31	24.93	20.16	19.71	17.20	9.52
Iron	3.16	6.45	4.12	4.89	5.25	52.66
Titanium	2.07	0.61	0.41	0.60	0.55	0.55
Calcium	5.33	16.62	6.90	7.94	14.97	3.36
Magnesium	0.80	1.09	1.37	1.54	3.42	0.18
Sodium	1.05	3.36	3.37	1.55	10.47	0.13
Pottasium	0.48	0.43	1.55	0.85	0.85	0.80
Barium	0.59	0.48	0.32	0.35	1.28	0.00
Strontium	0.09	0.13	0.11	0.11	0.44	0.00
Vanadium	0.05	0.07	0.06	0.05	0.06	0.00
Nickel	0.05	0.02	0.01	n/d	0.04	0.02
Phosphorus	0.34	0.00	0.08	0.06	0.00	2.19
Sulfur	2.31	1.10	1.65	3.52	10.57	1.60
Ash Fusion Properties [reducing atmos.]						
Initial Def.	1402.00	1196.00	1254.00	same	1104.00	1027.00
Softening	1466.00	1238.00	1274.00	as	1163.00	1043.00
Hemispherical	1477.00	1310.00	1363.00	Paint	1166.00	1049.00
Fluid	>1482.00	1352.00	1446.00	Earth	1213.00	1057.00

1) Analysis for Shell from Kovacik and Chambers (1988).

2) Analysis for Shell from Kovacik and Chambers (1988), corrected to 16.07% ash dry.

Appendix C Equations and conversion factors

Calculations and conversion factors

Conversion Factors

Imperial Unit	Multiply by	To get SI Unit
lb	0.4536	kg
lb/ft^3	16.02	kg/m^3
Btu/lb	2.324	MJ/T
Btu/ft^3	0.03723	MJ/m^3
ft^3	0.02832	m^3
short ton/day	907.2	tonne/day

Calculations

Gas Properties (at 15.6°C (60°F) and 101.36 kPa (14.696 psia))

	density (kg/m^3)	HHV (MJ/kg)	LHV (MJ/kg)
CO	1.182	10.10	10.10
H_2	0.0851	141.98	118.58
CO_2	1.873	0	0
CH_4	0.6760	55.49	49.95
others (assumed N_2)	1.190	0	0

Product Gas Heating Value (dry basis, 15/6°C)

Higher Heating Value

$$HHV\ (MJ/m^3) = (\%\ CO \times 11.938 + \%\ H_2 \times 12.08 + \%CH_4 \times 37.51) \div 100$$

Lower Heating Value

$$LHV\ (MJ/m^3) = (\%\ CO \times 11.938 + \%\ H_2 \times 10.09 + \%\ CH_4 \times 33.77) \div 100$$

Cold Gas Efficiency (based on HHV)

$$E\ (\%) = \frac{\text{HHV dry gas (MJ/m}^3\text{)} \times \text{volume dry gas (m}^3\text{)}}{\text{HHV maf coal (MJ/kg)} \times \text{feed rate maf coal (kg)}} \times 100$$

Carbon Conversion

$$\text{carbon conversion (\%)} = 100 \times \left[\frac{1 - \frac{\text{wt \% ash of coal}}{\text{wt \% ash of slag}}}{1 - \frac{\text{wt \% ash of coal}}{100}} \right]$$

where ash content is on dry basis